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# Soil & Tillage Research

Soil & Tillage Research 37 (1996) 67–75

Short Communication

# Soil bulk density, penetration resistance, and hydraulic conductivity under controlled traffic conditions [1]

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# Soil & Tillage Research

An International Journal on Research and Development in Soil Tillage and Field Traffic, and their Relationship with Land Use, Crop Production and the Environment
Published in Collaboration with the International Soil Tillage Research Organization (ISTRO)

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This implies research on: characterization or modeling of tillage and field traffic effects on the soil environment; the selection, adaption or development of tillage systems (including reduced cultivation and direct drilling) suitable for specific conditions of soil, climate, topography, irrigation and drainage, crops and crop rotations, intensities of fertilization, degree of mechanization, etc. and the appropriate use of tillage systems to maintain a balance between acceptable crop production, sustainability and minimum environmental impacts. In this context, papers on the characterization or modeling of tillage effects on: soil physical, chemical and biological properties, processes related to surface and subsurface groundwater quality, soil erosion, carbon and nutrient cycling and crop production, are most welcome. Papers on soil deformation processes, soil-working tools and traction devices, energy requirements and economic aspects of tillage are also considered. Attention will also be given to the role of tillage in weed, pest and disease control.



**Publication information:** *Soil & Tillage Research* (ISSN 0167-1987). For 1996 volumes 37-40 are scheduled for publication. Subscription prices are available upon request from the Publisher. Subscriptions are accepted on a prepaid basis only and are entered on a calendar year basis. Issues are sent by surface mail except to the following countries where air delivery by SAL mail is ensured: Argentina, Australia, Brazil, Canada, Hong Kong, India, Israel, Japan, Malaysia, Mexico, New Zealand, Pakistan, PR China, Singapore, South Africa, South Korea, Taiwan, Thailand, USA. For all other countries airmail rates are available upon request. Claims for missing issues should be made within six months of our publication (mailing) date. Please address all your requests regarding orders and subscription queries to: **Elsevier Science B.V., Journal Department, P.O. Box 211, 1000 AE Amsterdam, Netherlands, tel. (+31-20)4853642, fax. (+31-20)4853598.**

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Accepted 7 September 1995

**Abstract**

Adverse soil physical conditions that limit soil water infiltration, root development, and crop yield could develop when using a no-tillage system, especially in humid regions or for irrigated crops. This study determined the effects of tillage treatments and controlled traffic on soil bulk density (*BD*), penetration resistance (*PR*), hydraulic conductivity (*HC*), water content, and organic matter concentration. Treatments were no-tillage with residues left standing (NT-ResSt) or shredded (NT-ResSh), and no-tillage after wheat and conventional tillage after sorghum (NT-CT). Determinations were made at traffic furrow, non-traffic furrow, and row positions after grain sorghum (*Sorghum bicolor* (L.) Moench) harvest in 1992. The grain sorghum had been grown in rotation with winter wheat (*Triticum aestivum* L.) under limited irrigation conditions on Pullman clay loam (Torrertic Paleustoll) at Bushland, Texas, from 1986 to 1992. Tillage treatments did not significantly ($P = 0.05$) affect any determined variable. Mean *PR* was greatest (1.23 MPa) in the traffic furrow, but sampling position did not affect *BD*. Differences in *HC* were significant ($P = 0.05$) only due to sampling depth, but tended to be greater in row than in furrow positions and with the NT-CT treatment than with other treatments. These results show that adverse soil physical condition (increased *BD* and *PR*) development is limited to designated traffic zones when using no-tillage for irrigated crop production.

*Keywords:* Bulk density; Penetration resistance; Hydraulic conductivity; Conservation tillage; Conventional tillage; No-tillage; Controlled traffic

[1] Mention of trade or manufacture names is for information only and does not imply an endorsement, recommendation, or exclusion by the USDA-Agricultural Research Service.


*SSDI* 0167-1987(95)00508-0

## 1. Introduction

Conservation tillage, which involves maintenance of crop residues on the soil surface, effectively controls soil erosion (Harrold and Edwards, 1974; Langdale et al., 1979) and enhances soil water conservation (Mielke et al., 1986; Unger, 1984). In general, erosion control and water conservation increase with increasing amounts of crop residues retained on the soil surface.

Use of a no-tillage cropping system achieves greatest surface residue retention. However, there is concern regarding the potential for development of unfavorable soil physical conditions because the soil is not loosened by tillage when using no-tillage. Of particular concern are increased soil bulk density and penetration resistance, which, among other things, can reduce water infiltration, plant root growth, and crop yields. Concerns regarding development of adverse soil physical conditions are justified because equipment traffic (tractor, manure spreader, harvester, grain cart, etc.) associated with crop production operations increased soil bulk density and/or penetration resistance (Voorhees et al., 1985; Kayambo et al., 1986; Danfors, 1994). In these studies, factors such as equipment type, load per unit area (pressure on soil at the tire–soil interface), number of passes, soil type, and soil water content influenced the depth to which soil density and penetration resistance were increased. These factors also influenced the amount of density or resistance increase. Where these adverse soil conditions became sufficiently severe and were not alleviated by tillage, wetting and drying, or freezing and thawing, crop growth and yields were reduced.

Although highly variable, owing to the factors mentioned above, Arvidsson and Håkansson (1992) showed that plow layer compaction persisting after plowing reduced small grain cereal yields by 3.4% and sugar beet (*Beta vulgaris* L.) yields by 10.0%. Depending on soil profile and weather conditions during the growing season, heavy axle loads reduced silage maize (*Zea mays* L.) yield by up to 38% (Alblas et al., 1994). Average yield reductions were 15% with a 10 Mg axle load and 4% with a 5 Mg axle load. Danfors et al. (1992) placed the cost of annual and long-term effects of soil compaction at about \$96 ha$^{-1}$ when tractor tire inflation pressures were 70 kPa and \$170 ha$^{-1}$ when pressures were 150 kPa. These results indicate that use of proper management of crop production activities can reduce the potential for the development of adverse soil conditions due to compaction.

Compaction due to equipment traffic usually is of greatest concern. However, surface and subsurface soil density and penetration resistance may increase naturally when using a no-tillage system (Ehlers et al., 1983; Mielke et al., 1986). These increases result from raindrop impact and structural failure (collapse) of soils having low-stability aggregates. Soils with a high sand content are especially prone to develop a dense zone with a high penetration resistance (Awadhwal and Smith, 1990). With no-tillage, natural increases in density and penetration resistance usually are limited to the upper 15 cm of the soil profile.

Use of no-tillage rather than conventional (stubble mulch) tillage had no consistent effects on physical conditions of Pullman clay loam (fine, mixed, thermic Torrertic Paleustoll) under non-irrigated conditions in the US southern Great Plains (Unger and Fulton, 1990). Bulk density at the 0.04–0.07 m soil depth was greater in conventional tillage fields than in fields that were in no-tillage for 6 or 8 years. In contrast, penetration resistances were not significantly different in conventional and no-tillage (8 years) fields, but both had greater resistance than the field in no-tillage for 6 years. At the 0.14–0.17 m depth, density and penetration resistance differences were not significant.

Although tillage methods did not consistently affect soil physical conditions under non-irrigated conditions in the above study, it was hypothesized that localized zones of unfavorable conditions (increased bulk density and penetration resistance) could develop in an irrigated soil when all cultural operations are restricted to specified areas (controlled traffic). Objectives of this study were to compare the effects of controlled traffic in no- and reduced-tillage plots on bulk density, penetration resistance, and hydraulic conductivity of soil used for a winter wheat–grain sorghum rotation under limited-irrigation conditions. Soil water content and organic matter concentration were determined also.

## 2. Methods and materials

The study was conducted at the USDA Conservation and Production Research Laboratory, Bushland, Texas (3°11′N, 102°5′W, 1180 m above mean sea level). Average annual precipitation at Bushland is 475 mm (1939–1993), and average temperatures are 20.6°C maximum and 4.8°C minimum (1974–1993). Although the average minimum temperature is 4.8°C, air temperatures of about −20°C occur several times most winters in the region, which may result in soil freezing. The soil was Pullman clay loam, which contains 17% sand, 53% silt and 30% clay in the surface horizon (0–0.15 m depth) (Unger and Pringle, 1981). This soil has a moderate to high shrink–swell potential because it contains major quantities of montmorillonitic and illitic clays in all profile horizons (Taylor et al., 1963).

The study was on plots where winter wheat and grain sorghum were grown in rotation from 1986 to 1992. Determinations for this study were made only once (at the end of the rotation study in 1992) in plots from which grain sorghum was harvested in 1992. At the time of sampling, two cycles of the 3-year winter wheat–grain sorghum rotation had been completed. The rotation resulted in two crops in 3 years, with a 10–11 month fallow period between successive crops. Plots were leveled with a laser-controlled scraper before starting the study, then disk-bedded to form ridges and furrows at 1.0 m intervals. The soil water potential was below −1.5 MPa when the plots were leveled. Ridges were about 0.15 m high. Plots were 8 m wide and 40 m long.

Wheat drill row spacing was 0.25 m (four rows per ridge and furrow interval) and sorghum row spacing was 1 m (one row per ridge). Crops were flood irrigated when major water stress developed. Each plot was surrounded by berms to control irrigation water and to prevent precipitation water runoff and runon. Treatments, replicated three times, were no-tillage with residues left standing (NT-ResSt), no-tillage with residues shredded (NT-ResSh), and no-tillage after wheat and conventional tillage after sorghum (residues incorporated) (NT-CT). Residue heights were identical with all tillage treatments after harvest. Unger (1994) gave details of the rotation study and its effect on wheat and sorghum production. In that study, the standing- and shredded-residue treatments were imposed to determine whether residue orientation affected soil water storage during fallow and subsequent crop yields.

All equipment traffic (weed controlling, fertilizing, planting, and harvesting) in NT-ResSt and NT-ResSh plots was restricted to specified furrows throughout the 6-year study. Traffic in NT-CT plots was also restricted to specified furrows from final land preparation for wheat until sorghum harvest, but ridges and furrows were not maintained when conventional tillage (disking followed by disk-bedding to re-establish ridges and furrows) was performed during the fallow period after each sorghum crop. However, ridges and furrows in NT-CT plots were re-established at about the same position for each cycle of the rotation. Anhydrous ammonia was applied through chisel openers into all furrows to a depth of about 0.15 m before planting each crop.

Determinations in the field were made at traffic furrow, non-traffic furrow, and row positions. Bulk density (*BD*) and water content (*WC*) were determined from cores, 5.4 cm in diameter and taken to a 50 cm depth, at five locations for each position with a tractor-mounted, hydraulically powered sampler. Cores were separated into 10-cm-long segments, weighed, oven-dried at 105°C, and weighed again to determine *WC*. Penetration resistance (*PR*) was determined to 50 cm depth at ten locations at each position using a hand-held recording penetrometer (Bush Soil Penetrometer SP10, Findlay Irvine Ltd., Penicuik, UK) that had a 30° cone with a 12.8 mm diameter base.

To determine hydraulic conductivity (*HC*), cores 5.4 cm in diameter and 3.5 cm long were obtained from each furrow position at depths of 0–3.5 and 10–13.5 cm. For row positions, surface soil was removed so that sampling was at the same level as for furrow positions. Cores were kept in plastic bags and refrigerated until hydraulic conductivity (*HC*) was determined on eight cores from each position, depth, and treatment by the procedure of Klute (1965). Conductivities were determined for 0–1, 1–3, and 3–6 h periods. The *HC* data were scaled (Warrick et al., 1977) before statistical analysis. After determining *HC*, soil of the cores was dried at 60°C in an oven, then ground before determining organic matter concentration (OMC) by the modified Walkley–Black procedure (Jackson, 1958).

The study had a randomized block, split-split plot design. Tillage treatments were randomly assigned to whole plots, split plots were assigned to fixed sampling positions (traffic furrow, non-traffic furrow, or row), and split-split plots were associated with sampling depth. Data were analyzed by the analysis of variance technique (Statistical Analysis Systems Institute Inc., 1989). When the $F$-test showed statistical significance at the 5% level ($P = 0.05$) of probability, the protected least significant difference (Prot. LSD) procedure was used to separate means.

## 3. Results and discussion

Significance levels of $F$ values for the variables evaluated are given in Table 1. Tillage method (T) did not significantly affect any variable. Hence, data in Table 2 are for positions and depths averaged across tillage methods. Sampling position (P) affected *PR* and *WC* of field samples. All variables were affected ($P = 0.05$) by sampling depth

Table 1
Significance levels of $F$ values for soil variables as influenced by tillage treatment (T), sampling position (P), and sampling depth (D) in a controlled-traffic study for winter wheat and grain sorghum grown in rotation, Bushland, TX

| Soil variable | Significance level of $F$ value for | | | | | | |
|---|---|---|---|---|---|---|---|
| | T | P | D | P×D | T×D | T×P | T×P×D |
| *Field determinations* | | | | | | | |
| Bulk density | 0.5954 | 0.0823 | 0.0001 | 0.0001 | 0.2584 | 0.8848 | 0.8178 |
| Penetration resistance | 0.6990 | 0.0005 | 0.0001 | 0.0001 | 0.6702 | 0.5138 | 0.8978 |
| Water content | 0.8546 | 0.0130 | 0.0001 | 0.0016 | 0.9815 | 0.3496 | 0.8494 |
| *Laboratory determinations* | | | | | | | |
| Hydraulic conductivity | | | | | | | |
| 0–1 h | 0.5146 | 0.2000 | 0.0019 | 0.3202 | 0.3883 | 0.4204 | 0.4774 |
| 1–3 h | 0.3985 | 0.1562 | 0.0007 | 0.3431 | 0.3420 | 0.2493 | 0.2441 |
| 3–6 h | 0.3983 | 0.1851 | 0.0064 | 0.4049 | 0.3516 | 0.2957 | 0.2842 |
| Organic matter conc. | 0.3805 | 0.3121 | 0.0001 | 0.6560 | 0.1747 | 0.4856 | 0.1708 |

(D). All variables, except *HC* and OMC of laboratory cores, were affected by the P × D interaction. No variable significantly affected the T × D, T × P, or T × P × D interaction.

### 3.1. Large core or field determinations

Soil *BD* was affected only by sampling depth and the P × D interaction (Table 2). For the 0–10 cm depth increment, *BD* was greatest in the traffic furrow because of repeated traffic and least in the non-traffic furrow because of no traffic. Greater *BD* at the row position than at the non-traffic furrow position at the 0–10 cm depth is attributed to soil compression during crop planting, especially of sorghum that was planted on ridges where row sampling occurred. Increases in *BD* with depth are typical for Pullman soil (Unger and Pringle, 1981).

Differences in water content (*WC*) occurred mainly in the two upper increments where *WC* for the row position was lowest (Table 2). Lower water content at the row position is attributed to greater water use by sorghum at that position. Decreasing *WC* values with depth suggest that late growing-season or post-harvest rainfall may have partially replenished the soil water supply near the surface. Such rainfall may have contributed also to the greater *WC* near the surface at the furrow positions due to water accumulations. At a given depth below 20 cm, *WC* differences among positions were not significant. Mean *WC* values were similar for the two furrow positions, but both were or tended to be greater than for the row position.

Based on the *BD* and water content data shown in Table 2, the soil air content was low, which could lead anaerobiosis, especially after irrigation or precipitation on level plots surrounded by berms such as those used for this study. To minimize the potential for development of anaerobiosis on such plots, irrigations are limited to the amount of water that will infiltrate the soil in about 24 h. When major or prolonged precipitation

Table 2
Sampling position and depth effects on soil conditions in a controlled-traffic study for wheat and grain sorghum production, Bushland, TX

| Depth (cm) | Position | | | |
|---|---|---|---|---|
| | Traffic furrow | Non-traffic furrow | Row | Mean |
| *Bulk density: field ($Mg\ m^{-3}$)* | | | | |
| 0–10 | 1.52 | 1.40 | 1.45 | 1.46 |
| 10–20 | 1.51 | 1.52 | 1.50 | 1.51 |
| 20–30 | 1.51 | 1.50 | 1.51 | 1.51 |
| 30–40 | 1.54 | 1.55 | 1.53 | 1.54 |
| 40–50 | 1.57 | 1.55 | 1.57 | 1.56 |
| Mean | 1.53 | 1.50 | 1.51 | |
| LSD [a] (0.05): D, 0.02; P, NS; P×D, 0.04 | | | | |
| *Water content: field (% by volume)* | | | | |
| 0–10 | 40.5 | 41.2 | 38.2 | 40.0 |
| 10–20 | 38.9 | 40.1 | 38.3 | 39.1 |
| 20–30 | 37.3 | 37.3 | 37.4 | 37.3 |
| 30–40 | 36.5 | 36.9 | 36.7 | 36.7 |
| 40–50 | 35.8 | 35.4 | 36.0 | 35.7 |
| Mean | 37.8 | 38.2 | 37.3 | |
| LSD (0.05): D, 0.7; P, 0.6; P×D, 1.4 | | | | |
| *Penetration resistance: field (MPa)* | | | | |
| 5 | 0.62 | 0.30 | 0.47 | 0.46 |
| 15 | 0.88 | 0.56 | 0.64 | 0.69 |
| 25 | 1.30 | 1.23 | 1.04 | 1.19 |
| 35 | 1.58 | 1.65 | 1.63 | 1.53 |
| 45 | 1.79 | 1.89 | 1.69 | 1.79 |
| Mean | 1.23 | 1.13 | 1.04 | |
| LSD (0.05): D, 0.06; P, 0.08; P×D, 0.11 | | | | |
| *Hydraulic conductivity at 3–6 h: laboratory ($cm\ h^{-1}$)* | | | | |
| 0–3.5 | 0.62 | 1.15 | 2.06 | 1.28 |
| 10.0–13.5 | 0.08 | 0.11 | 0.33 | 0.17 |
| Mean | 0.35 | 0.63 | 1.20 | |
| LSD (0.05): D, 0.75; P, NS; P×D, NS | | | | |
| *Organic matter concentration: laboratory ($g\ kg^{-1}$)* | | | | |
| 0–3.5 | 18.3 | 17.2 | 17.1 | 17.6 |
| 10.0–13.5 | 14.3 | 13.8 | 14.2 | 14.1 |
| Mean | 16.3 | 15.5 | 15.7 | |
| LSD (0.05): D, 1.1; P, NS; P×D, NS | | | | |

[a] Least significant difference: D, depth; P, position; NS, non-significant.

occurs, the berms are breached to drain excess water from the plots. Anaerobiosis rarely is observed on Pullman clay loam under natural field conditions because excess water naturally drains from the land by surface flow.

Penetration resistance values at depths of 5, 15, 25, 35, and 45 cm were used for statistical analysis of the *PR* data. At 5 cm, *PR* was greatest in the traffic furrow and least in the non-traffic furrow (Table 2). At 15 cm, *PR* was greater in the traffic furrow than at other positions. It was greater at both furrow positions than at the row position at 25 cm. Differences at 35 cm were not significant, but *PR* was less at the row position than in the nontraffic furrow at 45 cm. Greater *PR*s at 5, 15, and 25 cm and the mean for the traffic furrow resulted from traffic being confined to that position during the 6 year study. Greater *PR* at 5 cm for rows than for non-traffic furrows is attributed to greater soil compression during crop planting, as mentioned previously. Reason for a significant difference at 45 cm is not apparent because differences at 35 cm were not significant. Mean *PR* was greatest for the traffic furrow position because of repeated traffic. It was least for the row position because no traffic occurred there and possibly because of greater root activity that loosened the soil. Under the soil water content conditions of this study, *PR* at no depth was as great as 2 MPa, the resistance at which cotton (*Gossypium hirsutum* L.) taproot penetration was about 40% compared with that where root penetration was not impeded (Taylor and Gardner, 1963). At lower water contents, *PR* would be greater, which could impede root penetration. Greater *PR*, however, may not be a serious problem on the Pullman soil because it has been observed that roots grow in shrinkage cracks as the water content decreases. The trends in *PR* due to traffic and soil depth were similar to those shown by Sommer and Zach (1992) and Dickson et al. (1992). Increases in mean *PR* with depth, in a general way, followed increases in mean *BD* and decreases in mean water content (*WC*) with depth. However, based on regression analysis, *PR* was related only to *WC* as given by

$$PR = 11.7 - 0.283WC \qquad r^2 = 0.788$$

The effect of *BD* on *PR* was not significant at the $P = 0.05$ level.

### 3.2. Laboratory determinations

Although *HC* was determined for 0–1, 1–3, and 3–6 h periods, data only for the latter period, which represent the steady-state condition, are shown in Table 2. For the 3–6 h period, differences in *HC* were significant at the $P = 0.05$ level only due to sampling depth (Table 1), with *HC* being greater for the 0–3.5 cm than for the 10–13.5 cm depth. These data indicate that water infiltration is impeded more by subsurface than by surface conditions of this soil. As a result, infiltration should be adequate so that a small application of water (precipitation or irrigation) will not cause runoff. However, large water applications could cause excessive runoff.

Soil OMC was significantly greater for the upper than for the lower sampling depth (Table 2). A sharp decline in OMC with depth is typical for Pullman clay loam (Unger and Pringle, 1981). Differences in OMC due to tillage methods and sampling positions were not significant (Table 1), but OMC tended to be greater on NT-ResSt and NT-ResSh treatment plots (only no-tillage) than in NT-CT plots and greater for the traffic furrow than for the other positions (data not shown). The trend due to positions probably resulted from the greater density of the traffic furrow soil that may have slowed microbiological activity and, hence, breakdown of surface residues and incorporation of residual organic materials with soil.

## 4. Conclusions

Soil bulk density and penetration resistance were greater in traffic furrow than in non-traffic furrow or row positions where no-tillage was used to produce winter wheat and grain sorghum in a rotation under limited irrigation conditions. These results support the hypothesis that localized zones of unfavorable conditions could develop in an irrigated soil when all cultural operations are restricted to specified areas (using controlled traffic). Although the increases occurred mainly in the furrows to which all crop production traffic was confined, some differences in *BD* and *PR* between non-traffic furrow and row positions were significant also. The results show that restricting all traffic to specified zones (controlled traffic) reduces the potential for development of adverse soil physical conditions under irrigated conditions when using a no-tillage cropping system. As shown in other studies (e.g. Dickson et al., 1992; Douglas et al., 1992), restricting all traffic to specified zones maintains the remaining soil in a non-compacted condition so that plant root development, and, hence, crop yields are not adversely affected.

## Acknowledgements

The assistance of L.J. Fulton, Biological Technician, in conducting this experiment and in statistical analysis of the data is gratefully acknowledged.

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 0167-1987/96/$15.00



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Printed in The Netherlands

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